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FINAL REPORT

THEORY OF THE TRAVELING WAVE TUBE

CONTRACT No. AF-19(122)-1
OCTOBER 31, 1953

NEW YORK UNIVERSITY

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Final Report

THEORY OF THE TRAVELING WAVE TUBE

Contract No. AF-19(122)-1

Morris Kline
Project Director

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I. Objectives of the Research.

Research on the theory of the traveling wave tube was initiated under contract number AF-19(122)-1 on November 10, 1948. This contract was granted to New York University by the Electronics Directorate of the Air Force Cambridge Research Center. Subsequent modifications of the contract extended the period of research to October 30, 1953. The present final report is an account of the objectives envisioned in 1948, the work done under the contract, conclusions reached, and suggestions for future research. It also contains a bibliography of theoretical articles on the subject of the traveling wave tube which have proved informative and helpful in the conduct of the research. The work was a continuation and expansion of some research on the traveling wave tube which was performed by members of our research group under a somewhat broader contract, number W 28-099-ac-170 granted by the Watson Laboratories of the Air Materiel Command, then at Red Bank, New Jersey (now in Rome, New York) to New York University. Research under this preceding contract was conducted from 1946 to 1948.

The object of the present contract was to undertake theoretical research on the subject of the traveling wave tube and allied topics. To utilize the potentialities of the research people involved the theoretical research was intended to be of a special character in two respects. First of all, we planned to tackle theoretical problems which would require the services of trained mathematicians rather than of engineers. That is, the essential difficulties in the research were to be mathematical ones. It is to be expected in the modern state of science that some problems would be amenable only to highly specialized mathematicians. Secondly, we attempted to do problems which would extend the general theoretical knowledge about the traveling wave tube and about the interaction of electron beams with electromagnetic fields. We did not seek to be engineering aides working alongside the experimentalist and doing calculations that might expedite experiments from day to day. That is, we did not seek to improvise approximate solutions of the immediate problems facing design engineers but

rather to explore ideas not yet pursued in practice and to extend and render precise knowledge gained by crude theoretical approximations and by experimentation. In general these objectives are the ones appropriate to basic applied mathematical research.

There is no need to emphasize the values that might accrue from theoretical work. However it may be well to point out what specific investigations were contemplated. By 1948 experimental models of the traveling wave tube had been built and operated, and some theoretical work had already been done. As mentioned above, our own group had already contributed to this earlier theoretical work. However the existing analysis of the modes which could propagate in a cold helix, that is, a helix not containing an electron beam, and in a helix with axial electron beams was approximate and incomplete. The reason for this state of affairs was simply that the problem of obtaining the structure of electromagnetic fields that could be supported by a helical wire, even in the absence of an electron beam, is a very difficult mathematical one and has not been solved exactly as yet. The theoretical research that had been performed on this problem employed idealizations of the helix that were crude in some respect or other. Either the space between the turns of the helix, or the thickness of the wire, or the conductivity of the wire, or the full range of the pitch angle was not included in the idealization. Efforts to obtain a better idealization of the helix and hence to learn more about the electric and magnetic fields that could be supported by a helix seemed warranted. Further, it was hoped that more could be learned about the higher modes and how any possible interference from them could be minimized. We envisioned, also, the study of the ranges of such parameters as current density, electron velocity, pitch angle, wire thickness and length of helix, within which amplification might take place, and the effect of such parameters on band width and noise. It was deemed important to learn what modes might be more easily excited by particular feeds such as a coaxial feed. Structures which might substitute for the helix, such as a wave guide with periodically spaced interior diaphrams, were also regarded as worthy of investigation.

Still another phenomenon which was tentatively included, time per-

mitting, was the interaction of electron beams traveling at different velocities and in the field of an electromagnetic traveling wave. As of 1948 this principle seemed to be worth exploring for incorporation in a new type of high frequency or ultra-high frequency amplifier or oscillator.

Since basic research often generates its own problems it was understood that any promising directions bearing on the general subject of the contract might also be pursued.

II. Completed Research.

The following research reports were completed under the contract and were submitted.

TW-9 Friedman, Bernard: Amplification of the Traveling Wave Tube, February, 1949.

TW-10 Sollfrey, William: Propagation Along a Helical Wire, June, 1949.

TW-11 Phillips, Ralph S.: The Electromagnetic Field Produced By a Helix, June, 1949.

TW-12 Friedman, Bernard and Malin, Henry: Excitation of the Traveling Wave Tube, February, 1950.

TW-13 Friedman, Bernard and Malin, Henry: Orthogonality Properties of the Modes of the Helical Wave Tube, October, 1950.

TW-14 Sollfrey, William and Weitz, Mortimer: The Gain and the Noise Figure of the Helical Traveling Wave Tube, April, 1951.

TW-15 Sollfrey, William: Effect of Initial Conditions on Traveling Wave Tubes, May, 1951.

TW-16 Friedman, Bernard: Eigenvalues of Compound Matrices, October, 1951.

TW-17 Keller, Herbert B. and Keller, Joseph B.: Eigenvalues of Nearly Circular Waveguides, December, 1951.

TW-18 Sollfrey, William: Magnetic Field Effects In Traveling Wave Tubes, May, 1952.

TW-19 Weitz, Mortimer L.: Propagation Constants of Traveling Waves, March, 1953.

TW-20 Parzen, Philip: Electromagnetic Wave Propagation in Bounded Electron Beams, May, 1953.

Among the research reports listed above, the following have been published. TW-9 appeared in the Journal of Applied Physics, April 1951. TW-10 appeared in the Journal of Applied Physics, July 1951. TW-11 appeared in the Quarterly of Applied Mathematics, October 1950. TW-17 has been accepted for publication in the Quarterly of Applied Mathematics. TW-20 is currently being submitted for publication. It is expected that a few of the other reports will also be published.

Attention is called to the following research reports which were completed by members of our research group under the preceding contract W28-099-ac-170 and which bear directly on the research performed on the present contract.

170-2 Phillips, R.S.: A Helical Wave Guide. January, 1947

170-3 Phillips, R.S. and Malin, H.: A Helical Wave Guide II. August, 1947

170-7 Phillips, R.S. and Malin, H.: Addendum to Research Report Number 170-3: Investigation of the Exceptional Modes. June, 1948

170-8 Friedman, B. and Malin, H.: Propagation in Wave Guides Bounded by Electrically Anisotropic Plates. July, 1948

III. Survey of the Completed Research.

We shall consider first those investigations which have sought to improve on the knowledge of the electromagnetic fields which can be supported by or can propagate along a helical wire. In these investigations no electron beam is taken into account and the helix is assumed to be infinitely long in both directions along its axis.

The investigations of this problem which were pursued under the present contract are a continuation of efforts made under a previous contract already referred to. Hence we shall first point out briefly the relationship of the present research to the earlier work. It has already been noted that the problem of obtaining electromagnetic fields which satisfy Maxwell's equations and the boundary conditions appropriate to a finitely conducting helical wire of non-zero thickness and arbitrary pitch has not been solved exactly; nor does it appear likely that this problem can be solved exactly. Hence all solutions of this problem which have been offered either approximate the true helix in some respect, as, for example, by assuming that the wire has zero thickness, or make approximations right after setting up the exact differential equations and boundary conditions. In the preceding contract, R. S. Phillips in Research Report Number 170-2 had considered a circularly cylindrical wave guide in which the helical effect is incorporated by having the wall of the guide perfectly conducting in the direction of the wire of a true helix with given pitch angle and perfectly non-conducting in the direction perpendicular to the helical one. This property was assumed to be present at each point on the wall of the guide. This idealization allowed no field outside the guide. The paper then obtained and described the modes which such an idealized helix could support. Moreover it showed how by the proper selection of design parameters the modes with axial phase velocity less than the velocity of light could be favored.

In Research Reports Numbers 170-3 and 170-7, R. S. Phillips and H. Malin considered an idealization of the helix which seems closer to the physical situation, namely, a circularly cylindrical wave guide which at each point on the surface is perfectly conducting in the direction which a true helix of given pitch might have, and perfectly non-conducting in a direction perpendicular to this one. However in this idealization the magnetic field was allowed to be non-zero outside and, of course, inside the guide, and

continuous through guide wall (of zero thickness). Again an analysis was made of the modes which can exist in such an idealized helix.

The second type of idealization, though better than the first one and though widely used by other investigations, is of course still far from the true physical helix. Hence investigations were continued under the present contract in an effort to obtain better mathematical representations of the true physical helix.

Among research efforts which were carried out under the present contract and which treat the problem of the cold helix, the first one was TW-10. W. Sollfrey undertook in this paper to take into account the thickness of the helix, a factor which had been neglected by other investigators, who assumed an infinitely thin wire. The basic plan of this paper was to introduce a new coordinate system such that the surface of the wire was one of the coordinate surfaces. Maxwell's equations were expressed in this system of coordinates and the boundary conditions presented by the perfectly conducting wire were readily expressible in this system. Because Maxwell's equations were too difficult to solve exactly in this coordinate system, an approximate solution was sought in the form of a series in which the variable was the ratio of the radius of the wire to distance between turns. Only the terms of this series involving the first power of the variable were retained. Physically this approximation corresponds to neglecting the proximity effects due to the coiling of the wire and indeed the resulting approximate solution shows the fields are comparable to those around a straight wire. The major result of the paper is that only the propagating modes have the velocity of light along the wire and therefore of course a smaller axial velocity depending upon the pitch. This result has been obtained by other methods. However the method of the paper is notable because no approximation involving the geometrical idealization of the helix itself or of the boundary conditions was introduced.

The research just described is also of mathematical interest because it employed a novel, non-orthogonal coordinate system excellently adapted to a helical wire. The analysis could have been carried farther by retaining higher powers of the variable in the series expansion. However, it was believed that the labor required to obtain this improvement in the result would have been too great to warrant the effort for the purposes of traveling wave tube theory. The problem of the tube rather than the cold helix also

involves an electron beam and with this factor included the whole analysis would have become unwieldly.

Still another attempt to obtain a better solution of the problem of the electromagnetic field supported by a helix was made by R. S. Phillips in TW-11. In this report the electromagnetic field produced by an infinitely thin perfectly conducting helix subject to a monochromatic excitation is investigated. The assumption is made that the effect of the monochromatic excitation would be to induce a sinusoidal electric current on the helical conductor and that this current travels along the helix with a real propagation constant β in the axial direction. The electromagnetic field for arbitrary β is in turn represented by means of the retarded vector potential. If the initial assumption as to the nature of the induced electric current is correct, then it seems possible to determine β so that the electrical field E_h vanishes in the helical direction on the helix. Because of the assumption of zero-thickness, this determination of β proved to be impossible. However, it was possible to define a β_o such that the ratio $E_h(\beta_o)/E_h(\beta \neq \beta_o)$ approaches zero as the helix is approached.

With the value of β_o it is possible to express the retarded potential as an integral and this integral is in turn expanded into a series of Bessel and Hankel functions. Since the field quantities E and H are obtainable from the retarded potential by differentiations, which are shown to be rigorously justifiable, the field expressions too are series of Bessel and Hankel functions. Finally the propagation constant β_o is determined so that the boundary conditions for the helix are satisfied. The precise expression for β_o is, in fact, equal to $\pm k\sqrt{a^2+\alpha^2}/\alpha$, where $k^2 = \varepsilon\mu\omega^2$, a = radius of the helix, and $\alpha = 2\pi$ times the distance between turns. The β_o so determined corresponds to the axial phase velocity one would obtain if the electromagnetic field traveled along the helix with the free space velocity of light.

One surprising result may be stated. For some values of k the system radiates. Radiating terms in the presence of a real β_o seems contradictory. However, calculations are made to show that the axial flow of energy is always infinite whereas radiating terms cause only a finite radial flow of energy per unit distance in the axial direction.

One may question the value of these numerous and varied idealizations of the physical helix but unfortunately this variety is necessary. Since

there is no exact and comprehensive theory of the helix as a guide for electromagnetic waves, each idealization gives some information. Moreover, each may be in error because of departures from the exact helix. Hence the various approximate treatments serve as a check on each other and each may serve to show the effect of one approximation rather than another. For example, the assumption that the helix is infinitely thin introduces some error. But the idealization which treats the helix of finite thickness, though it makes some other approximation such as perfect conductivity, may show that the inclusion of finite thickness does not alter the resulting fields too much.

Two other investigations under this contract also treated problems of the cold helix. Research Report TW-12 on "Excitation of the Traveling Wave Tube" treats the question of what modes must be present in the helix in order to match the lowest mode of a coaxial input to the helix and how the mode in the helix whose axial velocity is less than that of light can be favored. In this study the model of the helix used in report number 170-2 described above was employed. The matching conditions at the junction of the coaxial guide and the helix are that tangential E and H must be continuous.

Using the same model for the helix as in the previous investigation, Research Report TW-13 on "Orthogonality Properties of the Modes of the Helical Wave Guide" considered the problem of representing any given transverse field as a sum of the modes that can exist in such a helix. The paper shows by a study of what is commonly called the orthogonality properties of the modes that can exist in such a guide that any given arbitrary transverse field cannot be represented as a sum of the modes. However several subordinate results such as that the z-component of the power down the guide is the sum of the powers in the individual modes and that there cannot be complex (but there are imaginary) propagation constants were obtained.

A second group of studies concerned problems arising in the traveling-wave tube proper; that is, an electron beam is now presumed to be traveling axially along the helix and various questions concerning amplification, noise, and effect of surrounding magnetic field are considered. In the first of such studies, TW-9, "Amplification of the Traveling Wave Tube", the dependence of the amplification on certain parameters of the tube is obtained by

an explicit formula so that one can readily study the variation of amplification with variation in the parameters. This report improves on a result obtained by Chu and Jackson.* The model of the helix used by Chu and Jackson is that of a circular cylindrical surface of radius a at each point of which there is defined a fixed helical direction along which the current flow is constrained to move. It is also assumed that the electrons move within a cylinder of radius b concentric with the helical sheath. The fields are matched on the coaxial cylindrical boundary surfaces. If the fields are assumed to be circularly symmetric and vary with $e^{i\omega t - \gamma z}$, the transcendental equation for the propagation constant γ is found to be

$$i\,\frac{ka}{pa}\,\frac{\eta}{p}\,\frac{I_1(\eta\, b)}{I_o(\eta\, b)} = i\,\frac{ka}{pa}\left[\frac{I_1(pb) - K_1(pb)\left(\dfrac{\left(\frac{ka}{pa}\right)^2 \cot^2\theta\; I_1(pa)K_1(pa) - I_o(pa)K_o(pa)}{K_o^2(pa)}\right)}{I_o(pb) + K_o(pb)\left(\dfrac{\left(\frac{ka}{pa}\right)^2 \cot^2\theta\; I_1(pa)K_1(pa) - I_o(pa)K_o(pa)}{K_o^2(pa)}\right)}\right]$$

where

$$k^2 = \omega^2\varepsilon\mu,\quad k = \frac{2\pi}{\lambda} = \frac{\omega}{c},\quad p^2 = -(\gamma^2 + k^2),\qquad \eta^2 = p^2\left[1 + \frac{\frac{e}{m} I}{\pi b^2 \varepsilon\, v_o^3 (i\,\frac{\omega}{v_o} - \gamma)^2}\right]$$

$\frac{e}{m}$ = ratio of charge of electron to mass,

v_o = average value of the electron beam velocity,

I = d.c. beam current.

The above transcendental equation is well-nigh impossible to solve. By choosing a special set of parameters, Chu and Jackson reduce it to a cubic equation in the unknown p. The aim of report TW-9 may now be stated succinctly, viz., to reduce the transcendental equation to a cubic equation in p for <u>all</u> choices of the geometrical and physical parameters entering

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* See Chu and Jackson " Field Theory of Traveling Wave Tubes", Proc. I.R.E. Vol. 36, July, 1948, pp. 853-863.

therein.

The essence of the method employed is to consider the equation corresponding to the one given above but in a helix containing no electron beam, and then to obtain the roots of the above equation as a perturbation of the roots of the corresponding equation in the cold helix. A cubic equation is indeed obtained which has one real and two complex conjugate roots, one of which corresponds to the amplifying mode. If the geometrical parameters of the tube are fixed, then the amplification is seen to depend upon the voltage V of the electron beam. The dependence of amplification on V is then studied and some graphical results presented. Further, maximum amplification is also studied as a function of the ratio of the radius of the helix to the radius of the electron beam and as a function of pitch angle and frequency of the applied field. It is shown, finally, that no amplification occurs if the ratio of d.c. beam current to $V^{3/2}$ is too large.

The study of amplification and of noise is continued in Research Report TW-14. In this report assumptions as to the nature of the beam which are more realistic than those of other investigators are employed and the general formulas derived by Friedman in TW-9 are applied. Formulas and graphs are given which show the dependence of gain and noise on beam current, beam voltage, beam radius, and the frequency of the applied electromagnetic field. The results may be found in the report and are too detailed to be repeated here.

A third paper devoted to the theory of the traveling wave tube proper, TW-15, treats the effect of the excitation of the traveling wave tube on the operation of the tube. The effect of input field, input current, and input d.c. velocity on the field and current produced in the tube is obtained. Specifically, the input field, electron velocity, and electron current are supposed fixed or known at the point where the field and beam begin to travel along the helix, and the problems investigated are to find the field along the helix, the a.c. beam current, and the strength of the amplified wave in particular. Laplace transform theory is employed in this study. The transformation is with respect to z, that is, the variable along the axis, so that the initial data at $z = 0$ came into the study quite naturally. The major results of this paper are rather general formulas which can be applied to specific cases of exciting fields.

Many investigations of the traveling wave tube have assumed that an external magnetic field is applied which prevents the electron beam from spreading radially. All other effects of this magnetic field are ignored. In Research Report TW-18, the theory of the traveling wave tube is undertaken anew; this time the helix, represented as a circularly cylindrical wave guide conducting in the helical direction and supporting an electromagnetic field, the electron beam traveling radially along the axis of the helix, and an external magnetic field are considered together, and the possible modes that can exist in the helix are sought. The propagation constants of the possible modes are shown to be the roots of a quintic equation. The assumption is made in the derivation of the quintic that terms of second order and higher in v/c, where v is the electron velocity and c the velocity of light, are to be ignored. Three of these roots of this quintic are shown to be real so that the external magnetic field apparently does not introduce any new amplified waves beyond what were obtained by previous investigators who ignored the magnetic field in their theoretical approaches. Thus the effect of the external magnetic field must be to alter the value of the propagation constant of the amplifying mode. It was intended that this report should be followed by another investigation which would apply the general theory obtained to specific numerical examples and thereby render explicit the precise effect of the external magnetic field on the amplification. However time did not permit the undertaking of this investigation.

Further study of the possible values of the propagation constants which can occur for modes or waves in the usual traveling wave tube configuration, that is, a conducting cylindrical sheath or guide and a coaxial electron beam, has led to a result contained in Research Report TW-19. For rather general configurations it is proved that the phase velocity of an amplified wave must be less than the d.c. electron beam velocity. Specialization of the general configuration to the case of a d.c. beam in a perfectly conducting circular cylinder or a d.c. beam in free space shows that amplifying waves cannot occur in these cases. These last specialized results are, of course, intuitively very reasonable and readily predicted.

A general study of the possible modes and uniqueness of these modes in a bounded region containing an electron beam (TW-20) has shown that if we specify the component of the sinusoidal electric field tangent to the

boundary and the sinusoidal electron velocity or current density normal to the boundary, then the sinusoidal field quantities are determined uniquely. Application of this theorem to a right circular cylinder containing an electron beam moving with axial velocity only establishes the uniqueness of the modes. Moreover, the possible modes in this structure are obtained explicitly. The theory of this paper assumed a perfectly conducting boundary surface. Hence the theory is not strictly applicable as it stands to the structures used in traveling wave tubes. It is applicable to drift tubes and could be regarded as a step towards consideration of the same problem for structures such as helices.

In the course of our investigations centering about the traveling wave tube, questions concerning wave guides arose. Though no concerted effort along the lines of wave guide theory was regarded as desirable or possible under the present contract, whenever a seemingly profitable line of attack occurred, the problem was pursued. Two results were obtained and submitted.

One of these results, contained in Research Report Number TW-16, concerns the calculation of quantities involved in the design of rather complicated wave guide junctions. Mathematically expressed the quantities needed are the eigenvalues of high-order matrices. Since these matrices generally possess special symmetry properties it is possible to reduce the calculation of eigenvalues to the calculation of eigenvalues of lower-order matrices. This paper shows how the calculation may be so simplified.

The second result in the theory of wave guides, contained in Research Report Number TW-17, concerns the determination of the cut-off frequencies (eigenvalues) of almost circular, cylindrical wave guides. The principal result is the attainment of a better lower bound for the principal eigenvalue. This bound is in the form of an integral over a specially chosen circle related by a parameter to the almost circular boundary being investigated. The result is specialized and detailed but of appreciable theoretical importance. The theory of the paper is applied to a rectangular guide in order to show its accuracy.

IV. Suggestions For Further Research.

Through combined theoretical and experimental investigations it has been possible to build and operate successfully a variety of types of traveling wave tubes. Nevertheless the total picture of our knowledge of the traveling wave tube phenomenon is not too satisfactory. There are several reasons for this situation. In the first place no one has succeeded in giving an exact solution of the electromagnetic boundary-value problem presented by the helix, even without the electron beam. The various idealizations of the helix pursued by members of our research group and other investigators have approximated the helix. Though these approximations reinforce each other and hence add up to a reasonable account of the function of the helix as a carrier of electromagnetic waves, one does not have a completely accurate picture of all the modes. When the electron beam is taken into account further approximations as to velocity and current density are made in order to calculate the modes, amplification, and band width. The same is true when the presence of an external magnetic field is included. The accuracy of the present theoretical results is limited and the full potential of the ranges of operation of the tube are not known. Experimentation may answer some questions but of course always for the specific values of the parameters embodied in the tubes built.

When one considers the efficiency which has been attained in modern electronic devices, one realizes that mere satisfactory operation is not an acceptable level. Only when the full potentialities of power, amplification, band width, noise level, coupling to other circuit elements, and ease of operation have been attained can one affirm that the state of affairs is satisfactory. Further research on the cold helix and the helix with electron beam seems called-for along the lines pursued in the above reports and in comparable investigations.

A major limitation in all of the reports on the traveling wave tube submitted under this contract or written by almost all other scientists is the assumption of small signals. Generally speaking, small quantities, such as the ratio of beam velocity to the velocity of light and the ratio of a.c. beam current to d.c. beam current, are carried only to first order and the squares and higher powers of such quantities are dropped. The primary reason for making this type of approximation is that the resulting differential equations, partial or ordinary, become linear and it is then possible to

apply the extensive mathematical theory of linear differential equations. However, a fair amount of knowledge about non-linear differential equations is gradually being acquired and it seems entirely appropriate that a series of investigations assuming large signals be carried out. Only a few papers have been written on this aspect of traveling wave tube.

Because early workers on the traveling wave tube saw that a practical amplifier might be built around the helix, much of the subsequent theory and experimentation concentrated on the helix and succeeded in utilizing it successfully. However it is widely recognized that the essential action of the helix is to reduce the axial velocity of the electromagnetic field traveling on the helix so that it is about equal to the velocity of the electron beam which is sent along the axis. It is also widely recognized that other wave guide structures would serve the same purpose as the helix. However probably because other problems which arise in the use of any one of these alternative structures, e.g., methods of feeding, have not been solved, whereas these problems have been solved in the case of the helix, these alternative structures have not been considered too seriously. It is believed that more attention should be given to all devices which could slow down traveling electromagnetic waves and which would permit coupling with electron beams. As a perhaps somewhat extreme example, we mention an electron beam traveling over a dielectric surface whose dielectric constant is such as to slow up the phase velocity of an electromagnetic wave traveling over the surface.

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